Performance of Ultra-Wideband Transmission with Pulse Position Amplitude Modulation and RAKE Reception

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Abstract— Recently, pulse position amplitude modulation (PPAM) has been proposed for Ultra-Wideband (UWB) communication systems. PPAM combines pulse position modulation (PPM) and pulse amplitude modulation (PAM) to provide better performance and higher system capacity with low computational complexity. A RAKE receiver can make use of the rich multipath of UWB systems to improve system performance and capacity. In this paper we present the performance of a RAKE receiver employing maximal ratio combining (MRC) in a time hopping (TH) UWB system with PPAM modulation. Performance in a practical multipath fading channel is considered. The error probability and a union bound on performance are derived for a block fading environment. Numerical results are given to illustrate the system performance.

Keywords: RAKE Receiver, Ultra-Wideband, Pulse Position Amplitude Modulation, Time-Hopping

I. INTRODUCTION

In wireless communications, electromagnetic waves with an instantaneous bandwidth greater than 25% of the center operating frequency or an absolute bandwidth of 1.5 GHz or more are referred to as Ultra-Wideband (UWB) signals [1][2]. The basic concept of UWB is to transmit and receive an extremely short duration burst of radio frequency (RF) energy to implement high data rate transmission. Pulse amplitude modulation (PAM), pulse position modulation (PPM) and on/off keying (OOK) modulation are the most commonly used modulation schemes in UWB systems. PPM modulation uses the precise collocation of impulses in time to convey information, while PAM and OOK use the impulse amplitude for this purpose. UWB systems with PAM and PPM modulation have been extensively investigated [3][4][5][6].

In [7] a new modulation scheme, pulse position amplitude modulation (PPAM) was introduced. PPAM combines PPM and PAM constellations to provide a better tradeoff between system performance and complexity. In PPAM, a set of MN-ary signals are constructed from N-ary PPM signals by including M-ary PAM signals in the modulated dimension of the PPM signals. PPAM has been shown to have better performance than PAM and less complexity than PPM for the same data throughput for $MN > 2$. In particular, for $M = 2$, $2N$-ary orthogonal PPAM has better performance than $2N$-ary PPM with about half the computational complexity and the same data throughput.

Wireless communications systems typically operate in multipath fading channels. In addition to the direct path signal (if present), many reflected path signals can arrive at the receiver with different delays and attenuations, resulting in fading and intersymbol interference. Employing a RAKE receiver is an efficient means of overcoming these effects to achieve better performance [8][9]. Actually, one of the advantages of broadband wireless communication systems such as code division multiple access (CDMA) and UWB is the capability of utilizing multipath signals to improve system performance and capacity. Since UWB systems can resolve many paths they are rich in multipath diversity, so the use of RAKE diversity combining can be very effective. Considering the reasons given above, a RAKE receiver is a essential component of future UWB communication systems [10][11].

In this paper, we introduce RAKE receivers for UWB systems with PPAM modulation. The combining algorithm commonly used in RAKE receivers is maximal ratio combining (MRC) which is known to maximize the signal-to-noise ratio (SNR) for diversity channels [12]. To study the system performance from a practical perspective, the RAKE receiver combines only the L_c strongest signal paths out of the L resolvable paths. A practical multipath fading channel model is used to evaluate the system performance. The error probability and a union bound on performance are derived for a block fading environment. Numerical results are given to illustrate the system performance.

The remainder of this paper is organized as follows. Section II presents the PPAM signal structure and UWB multipath fading channel model. Section III gives the demodulation algorithm and the error probability and performance bounds are derived. Section IV provides some numerical results and finally, Section V presents a summary of the results.

II. SYSTEM MODEL

A. Signal Construction

The MN-ary PPAM signal $\mathbf{s}_{mn}$ is defined as an N-dimensional vector with nonzero value in the nth dimension [7]

$$\mathbf{s}_{mn} = [0, \ldots, 0, A_m\sqrt{E}, 0, \ldots, 0], \quad (1)$$

where $1 \leq n \leq N, 1 \leq m \leq M$, and $M > 1$, $A_m\sqrt{E}$ is one of the M possible PAM amplitudes with

$$A_m = 2m - 1 - M, \quad (2)$$

and

$$E = \frac{3E_{av}}{M^2 - 1}, \quad (3)$$

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1. REPORT DATE **01 JAN 2005**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Performance of Ultra-Wideband Transmission with Pulse Position Amplitude Modulation and RAKE Reception**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Electrical and Computer Engineering, University of Victoria P.O. Box 3055, STN CSC, Victoria BC, Canada, V8W 3P6**	8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001846, Applied Computational Electromagnetics Society 2005 Journal, Newsletter, and Conference.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**4**	

where E_{av} is the average energy of the transmitted signal.

A typical time hopping format for the signal of the kth user in a UWB system is given by [13]

$$s^{(k)} = \sum_{j=-\infty}^{\infty} A^{(k)} p(t - jT_f - c_j^{(k)} T_c - \delta d_{\lfloor j/N_s \rfloor}^{(k)}), \quad (4)$$

where $A^{(k)}$ is the signal amplitude, $p(t)$ represents the transmitted impulse waveform that nominally begins at time zero, and the quantities associated with (k) are transmitter dependent. T_f is the frame time, which is typically a hundred to a thousand times the impulse width resulting in a signal with very low duty cycle. Each frame is divided into N_h time slots with duration T_c. The pulse shift pattern $c_j^{(k)}$, $0 \leq c_j^{(k)} \leq N_h$, (also called the time-hopping sequence), is pseudorandom with period T_c. This provides an additional shift in order to avoid catastrophic collisions due to multiple access interference. The sequence d is the MN-ary data stream generated by the kth source after channel coding, and δ is an additional time shift utilized by the N-ary pulse position modulation. If $N_s > 1$ a repetition code is introduced, i.e. N_s pulses are used for the transmission of the same symbol. The received signal can be modeled as

$$r(t) = \sum_{k=1}^{K} s^{(k)}(t - \tau_k) + w(t), \quad (5)$$

where $w(t)$ is additive white Gaussian noise (AWGN) noise with power spectral density $N_0/2$ and τ_k is the propagation delay for the kth user. If only one user is present, the optimal receiver is an N-ary correlation receiver followed by a detector. When more than one link is active in the multiple-access system, the optimal receiver is a complex structure that takes advantage of all receiver knowledge regarding the characteristics of the multiple-access interference (MAI) [14]. However, for simplicity, an N-ary correlation receiver is typically used even when there is more than one active user. Note that for an MN-ary PPAM UWB system, N cross-correlators are required for demodulation. Compared with an MN-ary PPM UWB system, which requires MN cross-correlators for demodulation, the demodulation complexity is much lower.

B. Multipath Channel Model

In this paper we assume a multipath block fading channel. Specifically, fading is assumed to be constant during each channel coherence time, but becomes independent after one coherence time. This assumption is valid for high data rate broadband wireless communication systems such as UWB systems.

Considering a practical system model, we assume unequal average SNRs for the signal paths. We use an exponential decay power delay profile for the multipath model [15], so that the average SNR decreases as the path delay increases. Between different fading paths, we assume

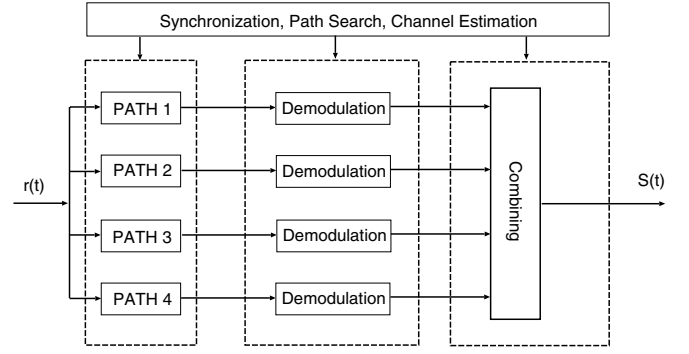$$\bar{\gamma}_l = \bar{\gamma}_0 e^{-\Delta l}, \quad (6)$$

Fig. 1. The structure of a RAKE receiver.

where $\bar{\gamma}_l$ is the average SNR of the lth path, and Δ is a constant between 0 and 1. Based on (6), we have $\bar{\gamma}_1 > \bar{\gamma}_2 > \ldots > \bar{\gamma}_L$.

For each path, we use the statistical fading model for indoor transmission first introduced in [16]. This model employs a $\Gamma(\Omega; m)$ function to model the channel fading where Ω is the received normalized symbol energy and m is a constant indicating the depth of fading, which is between 1 and 6 and decreases as the path delay increases. Since the fading is slow, we assume the receiver can obtain the multipath power delay profile and the average received signal power E_{rx} by channel estimation. The channel impulse response over the observed time interval is $h_i(t)$ with $1 \leq i \leq L$.

A RAKE receiver is essentially a set of individual correlators (fingers). Because of hardware complexity constraints and system delay limits for high speed systems, and also considering the large number of signal paths in UWB systems, it is not practical to implement the same number of fingers as the number of resolvable paths. We assume that there are L_c fingers available in the RAKE receiver. Under this assumption, the receiver will only combine L_c selected paths from all L resolvable paths. Fig. 1 shows the structure of a RAKE receiver with four fingers, i.e. $L_c = 4$. The selected signals on each finger are correlated with the despreading sequence and integrated over the symbol interval. The outputs from the fingers are then weighted according to the MRC algorithm and combined to form the receiver output.

The paths selected for the L_c fingers in the RAKE receiver are updated periodically, usually at the rate of the channel coherence time. By performing less compare operations and combining only those paths with high SNR, energy usage is reduced and the mobile terminal battery life is increased. We can also avoid the increased noise caused by combining paths with very poor SNR.

III. RAKE RECEIVER FOR PPAM MODULATION

A. Demodulation Scheme

The UWB channel has frequency selective fading which can be modelled by a linear tapped-delay-line [17]. Here we consider a block fading channel with L paths

$$\mathbf{h(t)} = [h_1(t), h_2(t), \ldots, h_L(t)], \quad (7)$$

where $h_i = \alpha(\tau_i)e^{-j\tau_i}$ denotes the complex path channel response, and τ_i is the time delay of the ith path. The received signals are

$$\mathbf{r}(t) = \sum_{k=1}^{K} s^{(k)}(t - \tau_k) * \mathbf{h(t)} + \mathbf{w}(t). \qquad (8)$$

Note that $\mathbf{h(t)}$ includes both small scale channel fading and power path loss. For frames within one fading block, let

$$\mathbf{g}^{(k)}(t) = s^{(k)}(t - \tau_k) * \mathbf{h(t)}, \qquad (9)$$

and rewrite (8) as

$$\mathbf{r}(t) = \sum_{k=1}^{K} \mathbf{g}^{(k)}(t) + \mathbf{w}(t). \qquad (10)$$

For N-dimensional orthogonal signals, the receiver has a parallel bank of N cross-correlators. Let $\mathbf{z}^j$, $1 \leq j \leq N$, denote the jth basis signal vector,

$$\mathbf{z}^j = [0, \ldots, 0, 1, 0, \ldots, 0], \qquad (11)$$

where the nonzero value is in the jth dimension. The optimum detector makes a decision in favour of the signal corresponding to the crosscorrelator with the minimum Euclidean distance

$$C(\mathbf{r}, \mathbf{z}^j) = \mathbf{r} \bullet \mathbf{z}^j = \sum_{q=1}^{N} \mathbf{r}(q)\mathbf{z}^j(q). \qquad (12)$$

Note that both $\mathbf{r}(q)$ and $\mathbf{z}^j(q)$ are the qth elements of the corresponding vectors. We have

$$C(\mathbf{r}, \mathbf{z}^j) = w^j, \qquad (13)$$

when $j \neq n$ and

$$C(\mathbf{r}, \mathbf{z}^n) = A_m \sqrt{E \|\mathbf{h(n)}\|^2} + \|\mathbf{h(n)}\| w^n, \qquad (14)$$

when $j = n$. In (14) we have

$$\|\mathbf{h(n)}\| = \sqrt{\sum_{n=1}^{N} \alpha(n)^2}, \qquad (15)$$

and $\|\mathbf{h(n)}\| w^n$ has a Gaussian distribution as $\|\mathbf{h(n)}\|$ is a constant over the demodulation time window from the block fading assumption. For convenience define

$$N_0^* = \|\mathbf{h(n)}\|^2 N_0. \qquad (16)$$

Thus (14) can be viewed as an AWGN equivalent channel as the fading block is larger than our demodulation window. The demodulated The optimum detector output is

$$\hat{\mathbf{s}} = \underset{s_{ij}}{\text{argmin}} \|C(\mathbf{r}, \mathbf{z^j}) - A_i \sqrt{E^*}\|, \qquad (17)$$

where $i = 1, 2, \ldots, M$ and $j = 1, 2, \ldots, N$ [18] and

$$E^* = \frac{3E_{rx}}{M^2 - 1}. \qquad (18)$$

$A_i \sqrt{E^*}$ is one of the M possible PAM amplitudes after the average amplitude threshold adjustment considering the power loss during transmission.

B. Error Probability and Union Bound

We now derive the error probability and union bound for the TH UWB system with a RAKE receiver based on the AWGN equivalent channel model described by (14). The error probability of a PPAM signal over a block fading channel is

$$P_{MN} = 1 - P_c, \qquad (19)$$

where

$$\begin{aligned} P_c = & \frac{1}{M} \int_{-\infty}^{B} \left(\frac{1}{\sqrt{2\pi}} \int_{-A}^{A} e^{-\frac{x^2}{2}} dx \right)^{N-1} p(r_m) dr_m \bigg|_{m=1} \\ & + \frac{1}{M} \sum_{m=2}^{M-1} \int_{C}^{B} \left(\frac{1}{\sqrt{2\pi}} \int_{-A}^{A} e^{-\frac{x^2}{2}} dx \right)^{N-1} p(r_m) dr_m \\ & + \frac{1}{M} \int_{C}^{\infty} \left(\frac{1}{\sqrt{2\pi}} \int_{-A}^{A} e^{-\frac{x^2}{2}} dx \right)^{N-1} p(r_m) dr_m \bigg|_{m=M}. \end{aligned}$$
$$(20)$$

In (20) we have $A = |\frac{r_m}{\sqrt{N_0^*/2}}|$, $B = (A_m + 1)\sqrt{E^*}$, $C = (A_m - 1)\sqrt{E^*}$ and

$$P(r_m) = \frac{1}{\sqrt{\pi N_0^*}} \exp\left(-\frac{(r_m - A_m\sqrt{E^*})^2}{N_0^*} \right). \qquad (21)$$

P_{MN} is the instantaneous symbol error rate. To get the average system symbol error rate, we can average (19) over the probability density function (PDF) of the channel $p(\mathbf{h})$

$$P_{average} = \int P_{MN}(\mathbf{h})p(\mathbf{h})d\mathbf{h}. \qquad (22)$$

Based on (19), the union bound is

$$P_{MN} < \frac{N-1}{\sqrt{2}M} \sum_{m-1}^{M} e^{-\frac{\|\mathbf{h(n)}\|^2 A_m^2 E^*}{2N_0^*}} + 2Q\left(\sqrt{\frac{2E^*}{N_0^*}} \right). \qquad (23)$$

Since an error can only occur in one direction when either one of $\pm(M - 1)$ is transmitted, a tighter bound is given by

$$P_{MN} < \frac{N-1}{\sqrt{2}M} \sum_{m-1}^{M} e^{-\frac{\|\mathbf{h(n)}\|^2 A_m^2 E^*}{2N_0^*}} + \frac{2(M-1)}{M} Q\left(\sqrt{\frac{2E^*}{N_0^*}} \right). \qquad (24)$$

Using

$$Q(x) < e^{\frac{x^2}{2}}, \qquad (25)$$

the bound can be simplified to

$$P_{MN} < \frac{N-1}{\sqrt{2}M} \sum_{m-1}^{M} e^{-\frac{\|\mathbf{h(n)}\|^2 A_m^2 E^*}{2N_0^*}} + \frac{2(M-1)}{M} e^{-\frac{E^*}{2N_0^*}}. \qquad (26)$$

IV. NUMERICAL RESULTS

In this section, the error probability is evaluated for a RAKE receiver in a UWB systems with PPAM modulation. We also compare the performance with PAM and PPM systems. We consider 2×2 PPAM, i.e. $M = 2$ and $N = 2$, and use Gaussian first derivative pulses for the UWB signals. We do not consider inter-symbol-interference here.

Fig. 2 shows the symbol error probability in multipath fading with different numbers of RAKE fingers. This figure shows that the system performance improve as the number of fingers is increased. However, the most significant improvements occur for the first 2-4 fingers, which nicely fits our exponential decay power delay profile assumption. Note that for typical SNR values, the curves for $L_c = 8$ and $L_c = 12$ are very close.

Fig. 3 compares the performance of PPAM, PAM and PPM with a RAKE receiver over the same fading environment. Here we have $L_c = 8$ and $L = 12$. Fig. 3 shows that 2×2 PPAM has better performance than 4-PAM and almost the same performance as 4-PPM. However, 2×2 PPAM has only about half of the computational complexity of 4-PPM with similar performance. Given this fact, 2×2 PPAM is an attractive choice for UWB communications.

V. SUMMARY

In this paper, we considered a RAKE receiver in a UWB system with PPAM modulation. A practical multipath fading channel model was used to evaluate the system performance. The error probability and a union bound on performance were derived for a block fading environment. Numerical results were given to illustrate the system performance. The approach used in this paper can easily be generalized to similar UWB systems with other forms of diversity.

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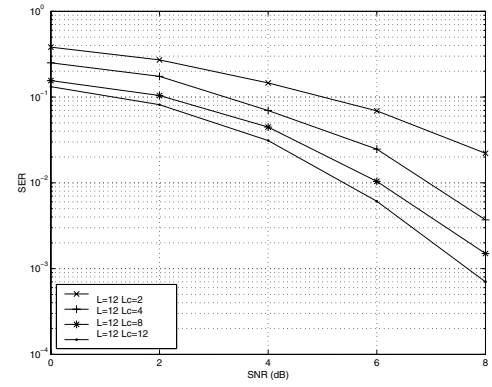
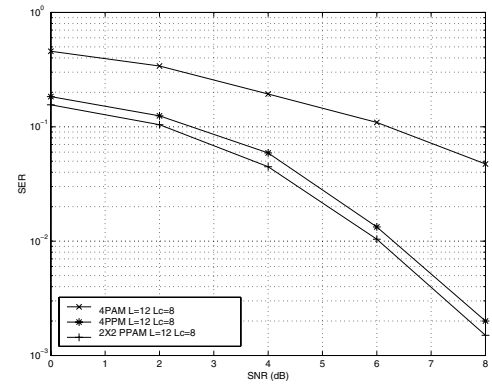Fig. 2. 2×2 PPAM performance with different numbers of RAKE fingers.

Fig. 3. 4-PAM, 4-PPM and 2×2 PPAM performance with a RAKE receiver.

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